NACA

CLASSIFICATION CHANGED

RESEARCH MEMORANDUM

To UNCLASSIFIED

By authority of Nasa TPA 11 Date Effective 12-1-59

MB 2-1-60

BEHAVIOR OF THE BELL X-1A RESEARCH AIRPLANE DURING EXPLORATORY FLIGHTS AT MACH NUMBERS NEAR 2.0 AND AT EXTREME ALTITUDES

By Hubert M. Drake and Wendell H. Stillwell

High-Speed Flight Station
Edwards, Calif.

CLASSIFICATION CHANGED

~~CONFIDENTIAL~~

To

By authority of ~~TRN-118~~ Date Effective ~~7-26-57~~

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

September 1, 1955

 [redacted] [redacted]

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

BEHAVIOR OF THE BELL X-1A RESEARCH AIRPLANE DURING EXPLORATORY FLIGHTS AT MACH NUMBERS NEAR 2.0 AND AT EXTREME ALTITUDES

By Hubert M. Drake and Wendell H. Stillwell

SUMMARY

A flight program has been conducted by the U. S. Air Force consisting of exploratory flights to determine the Mach number and altitude capabilities of the Bell X-1A research airplane.

On two flights of the X-1A airplane, one reaching a Mach number of about 2.44, the other a geometric altitude of about 90,000 feet, lateral stability difficulties were encountered which resulted in uncontrolled rolling motions of the airplane at Mach numbers near 2.0. Analysis indicates that this behavior apparently results from a combination of low directional stability and damping in roll and may be aggravated by high control friction and rocket motor misalignment. The deterioration of directional stability with increasing Mach number can lead to severe longitudinal-lateral coupling at low roll rates. The misalignment of the rocket motor could induce sufficiently high roll velocities to excite these coupled motions. Adequate control of these motions was virtually impossible because of the high control friction. In the absence of rolling, poor lateral behavior might be expected at somewhat higher Mach numbers because wind-tunnel data indicate neutral directional stability at about $M = 2.35$.

INTRODUCTION

An expedited flight program has been conducted at Edwards Air Force Base, Calif. to determine the Mach number and altitude capabilities of the Bell X-1A research airplane. This program was carried out by the U. S. Air Force with operational assistance provided by Bell Aircraft Corp. At the beginning of this program the National Advisory Committee for Aeronautics provided instrumentation assistance by furnishing airspeed and acceleration recorders.

[redacted]

Poor dynamic lateral stability characteristics, resulting from the decrease in directional stability with increasing Mach number (ref. 1), were experienced during a previous investigation with a highly loaded airplane at high altitude and high Mach number. It was expected, therefore, that poor stability characteristics might also be encountered during the X-1A flight program. On the second flight of the program, which was an attempt to attain maximum Mach number, violent uncontrolled motions were encountered at a Mach number of about 2.2. Because of this incident, the Air Force requested that the NACA assist the program by installing complete handling qualities instrumentation and by rendering engineering assistance.

The Air Force high altitude program was then instituted and several flights were made in an attempt to reach maximum altitude. On one flight of this program a Mach number of about 2.0 was reached without encountering unusual stability and control problems. However on the succeeding attempt to attain maximum altitude, at a Mach number of about 2.0, the uncontrolled behavior was again encountered.

SYMBOLS

a_l longitudinal acceleration, g units

a_n normal acceleration, g units

a_t transverse acceleration, g units

C_l rolling-moment coefficient

C_{l_β} variation of rolling-moment coefficient with sideslip angle, $dC_l/d\beta$, per deg

C_{N_A} airplane normal-force coefficient, a_nW/qS

C_n yawing-moment coefficient

C_{n_β} variation of yawing-moment coefficient with sideslip

g acceleration due to gravity, ft/sec^2

h_p pressure altitude, ft

I_X moment of inertia about longitudinal stability axis, $slug\text{-}ft^2$

I_Y	moment of inertia about lateral stability axis, slug-ft^2
I_Z	moment of inertia about vertical stability axis, slug-ft^2
i_t	stabilizer incidence, deg
F_a	aileron stick force, lb
F_e	elevator stick force, lb
F_r	rudder pedal force, lb
M	Mach number
P	free-stream static pressure, lb/sq ft
p	rolling velocity, radians/sec
q	dynamic pressure, $0.7M^2P$, lb/sq ft
q	pitching velocity, radians/sec
r	yawing velocity, radians/sec
S	wing area, sq ft
t	time, sec
W	weight, lb
α	angle of attack, deg
β	angle of sideslip, deg
δ_{a_L}	left aileron position, deg
δ_e	elevator position, deg
δ_r	rudder position, deg
ω	frequency, radians/sec

Subscripts:

θ	pitch
ψ	yaw

AIRPLANE

The X-1A is a single-place rocket-powered research airplane having a straight 8-percent-thick wing and a straight 6-percent-thick tail. The X-1A differs from the original X-1 airplane by having a modified cockpit configuration, a longer fuselage to accommodate additional propellant tanks, and a turbine-driven propellant-pump system. The added propellants result in a total powered time of approximately 4.2 minutes at full thrust which gives the airplane considerably greater performance potential over the earlier model which had a total powered time of about 2.5 minutes.

A three-view drawing of the X-1A is shown in figure 1 and a three-quarter front-view photograph is presented in figure 2. Contained in table I are pertinent airplane dimensions and characteristics.

The control surfaces do not incorporate aerodynamic balance or power boost. The horizontal stabilizer is adjustable, being driven by a screw jack. Only one rate of surface deflection is available. The elevator control contains a centering spring to improve the control-force gradient at low speeds. Figure 3 presents no-load measurements of the control system friction, made by measuring the control positions and control forces as the controls were slowly deflected. The large amount of friction in these systems should be noted.

INSTRUMENTATION

Instrumentation installed for the flights reported in this paper were not identical. For flight A, the flight to maximum Mach number, the recording instrumentation consisted of a Bell Aircraft photopanel, an NACA airspeed-altitude recorder, and an NACA three-component accelerometer. The Bell Aircraft photopanel instrumentation was used to record the following quantities:

Elevator position
Rudder position
Left aileron position
Stabilizer position
Rolling velocity
Pitching velocity
Yawing velocity

The photopanel instruments were photographed by a 35 millimeter camera which operated at a rate of four frames per second.

Airspeed and altitude were measured by an NACA high-speed pitot-static head located as shown in figure 4(a). This head was equipped with a type A-6 (ref. 2) total pressure pickup. The extremely short nose boom was necessitated by the clearance of the X-1A when coupled to the B-29 drop airplane.

Standard NACA recording instruments were installed to record the following quantities during flights B and C to maximum altitude:

Airspeed
Altitude
Vertical acceleration
Longitudinal acceleration
Transverse acceleration
Elevator position
Left aileron position
Right aileron position
Rudder position
Stabilizer position
Elevator stick force
Aileron stick force
Rudder pedal force
Pitching velocity
Rolling velocity
Yawing velocity

In addition, 16-millimeter GSAP cameras were installed to photograph the horizon forward and to the left of the airplane. These cameras operate at a rate of four frames per second and enable the airplane attitude to be determined during flight.

Airspeed and altitude were measured by an NACA high-speed pitot-static head, with a type A-6 total pressure pickup, which could be extended in flight to the position shown in figure 4(b). Angles of attack and sideslip were measured by vanes mounted on the extensible nose boom.

The pilot's instruments were connected to the left wing boom pitot-static head during all flights.

AIRSPEED CALIBRATION

The extremely short nose boom used for flight A resulted in large errors in the measured static pressure at subsonic and transonic speeds and airspeed-calibration data were not obtained during the two flights in which this boom was used. However, an estimated calibration has been made based on the calibrations of other airplanes with nose-boom installation. Although none of these airplanes have nose booms as short as that of the X-1A, it is believed this estimated calibration is accurate to approximately $M = \pm 0.05$. Mach numbers below the calibration discontinuity (jump), which occurs at about $M = 1.25$, have been corrected according to this estimated calibration. Mach numbers above the discontinuity are uncorrected because the error at supersonic speeds is believed to be negligible at small angles of attack and sideslip.

Airspeed-calibration data were obtained at subsonic and transonic speeds, for the nose-boom installation utilized during flights B and C, by the radar tracking method of reference 3. Limited airspeed-calibration data obtained at supersonic speeds indicate that the static-pressure error is negligible at small angles of attack and sideslip. It is believed that the Mach numbers for flight B are accurate to approximately $M = \pm 0.01$.

During the uncontrolled maneuvers that occurred during these two flights, the airplane encountered large angles of attack and angles of sideslip which produced large fluctuations in the static pressure. The pressure altitudes and Mach numbers are in error by an unknown amount during these periods.

TESTS, RESULTS, AND DISCUSSION

This paper presents data obtained during three flights of the X-1A airplane: flight A, a flight to high Mach number piloted by Major Charles E. Yeager, and flights B and C, flights to high altitude piloted by Major Arthur Murray.

A time history of Mach number, altitude, and normal-force coefficient for flight A is shown in figure 5 for the period from launch to about 5 seconds before the uncontrolled motions started. The X-1A was launched at an altitude of about 30,500 feet. Three rockets were fired about 10 seconds after launch and the fourth rocket was fired at about 45,000 feet during the climb. A pushover was started at about 70,000 feet which resulted in level flight at 76,000 feet, the altitude at which the high-speed run was made.

Time histories of all measured quantities for times subsequent to figure 5 are shown in figure 6. These data, except the accelerations, altitudes, Mach numbers, and C_{N_A}, were furnished by the Bell Aircraft Corp. as obtained from their flight recorder. During this flight the normal acceleration recorder was subject to intermittent sticking and the transverse acceleration recorder was off scale several times; however, where they are shown, these quantities are believed to be reliable. A post-flight instrument inspection revealed that the rate-of-pitch and rate-of-yaw indicators were damaged during the flight. It is not known at what time during the flight the damage occurred, therefore the magnitude of the values shown on the time history may be in error. Nevertheless it is believed the data are suitable for qualitative indications.

In the first portion of figure 6 the airplane is in steady, controlled flight with about 7° of rudder and 1° of aileron required for trim. This large out-of-trim condition has been encountered during all flights of the X-1A and will be discussed in a following section of this paper. At about time 284 seconds a slow rolling motion to the left started and aileron, then rudder, were applied for control. The airplane responded, but apparently too much control was applied and the airplane commenced rolling more rapidly to the right. In attempting to correct for this condition, the control movements caused the airplane to snap abruptly into a rapid roll to the left. The rockets were shut off and almost immediately a peak recorded value of $M = 2.47$ was reached. A reasonable fairing of the oscillatory airspeed-altitude record indicates an average Mach number of 2.44 during this period. (See appendix.) The uncontrolled motions of the airplane resembled an oscillatory spin with large normal and transverse accelerations encountered and with periodic reversals of roll direction.

During these violent motions, full airplane nose-up stabilizer was applied at time 324 seconds which caused a high g level to be reached and maintained until recovery was effected. The airplane lost altitude rapidly and decelerated during these gyrations, ending finally in a spin at subsonic speeds. Recovery from the spin was effected at about 25,000 feet.

Figure 7 presents time histories of Mach number, altitude, and normal-force coefficient for flight B for the period from launch to about 5 seconds before the uncontrolled motions started. The flight during this initial period is similar to flight A except, since the objective of this flight was to attain high altitude, the climb was continued above 75,000 feet. Presented in figure 8 are time histories of all the measured quantities for a period subsequent to the times of figure 7. The sideslip angle recorder was subject to intermittent sticking during the flight, however the data are believed to be reliable where shown on the time history.

An inspection of the horizon camera records indicated that roll angles of about -3° to 5° were encountered during the climb as a result of control motions. At about time 284.5 seconds, a roll to the left to about 10° was encountered which was corrected by aileron and rudder control application. The airplane responded and rolled toward a level attitude. The aileron was then moved to stop the rolling and rudder pedal force was reduced to return the rudder to the trim position. The rudder moved very little, however, and did not regain its trim position until the rudder pedal force was reduced from a peak value of 70 pounds, right, to almost zero. The rudder moved abruptly from trim position, approximately 6° right, to about 1° left with the application of about 20 pounds left rudder pedal force. This overcontrolling, apparently due to excessive friction, caused development of a considerable rate of roll of about 2 radians per second.

The rockets were cut and the airplane continued to climb while rolling out of control, reaching a peak recorded pressure altitude of about 89,000 feet. This value was obtained at a peak in the static pressure fluctuations, and radar data, used for determining the maximum geometric altitude, were not obtained above about 85,000 feet. After fairing the pressure altitude data and correcting for the difference between pressure and geometric altitude encountered at 85,000 feet, it appears that a maximum geometric altitude of about 90,000 feet was reached. (See appendix.)

The motions and accelerations during flight B were not as violent as during flight A, apparently because of the higher altitude and lower Mach number. Also, the previous occurrence of this behavior in flight A enabled the pilot of flight B to anticipate the control required if the same trouble were encountered. By using the rudder and ailerons, he was able to control the motions to some extent; however, it was apparently very easy to overcontrol. Recovery was finally effected at about 65,000 feet and at a Mach number of about 1.76.

Subsequent to these flights, wind-tunnel tests were performed in the Langley 9-inch supersonic tunnel on a model of the X-1A. These tests (unpublished) showed that both the directional stability and damping in roll are very low at Mach numbers above about 2.0. The directional stability at zero lift was found to be zero at about $M = 2.3$.

Considering the lack of directional stability at Mach numbers near 2.3, it is not surprising that the airplane encountered uncontrollable motions on flight A. At $M = 1.97$, however, the speed at which difficulty was encountered on flight B, the airplane has a value of C_{n_β} at zero angle of attack of about 0.0008 per degree which formerly was considered sufficient for airplanes of the general configuration of the X-1A. However, the value of C_{n_β} required for stability is critically dependent upon the mass distribution and the values of the other stability derivatives. At high rates of roll, inertial coupling may be sufficiently strong to require a considerably larger value of C_{n_β} for stability. Therefore lateral difficulty may be experienced at the value of C_{n_β} indicated by the tunnel tests, and if, as is probable, C_{n_β} is reduced by increasing angle of attack (shown in tunnel tests of other configurations, ref. 4), lateral difficulties are even more likely.

A rather simplified analysis of the inertial coupling is reported in reference 5. Such an analysis has been applied to the X-1A at $M = 2.0$ by W. H. Phillips of the Langley Laboratory as follows: For a Mach number of 2.0, C_{m_α} was assumed as -0.027 per degree, and C_{n_β} was assumed 0.001 per degree. These values yield values of $\omega_\theta = 2.36$ radians/sec and $\omega_\psi = 1.06$ radians/sec for the frequencies of the nonrolling airplane. The oscillation frequencies of the rolling airplane are obtained by the method of reference 5 and are presented as a function of rolling velocity in figure 9. As figure 9 shows, the short period (pitch) mode increases in frequency with rolling, whereas the long period (yawing) mode initially decreases in frequency as rolling velocity increases. As indicated in figure 9 the long period mode becomes unstable at a rate of roll of about 1.15 radians/sec and becomes stable again at 2.4 radians/sec, whereas at still higher rates of roll the frequency increases from zero. During rolling, both modes will appear in the pitch and yaw records. The critical roll velocities would be reduced if, as appears likely, the true value of C_{n_β} were less than 0.001.

From this analysis, a tentative explanation of the X-1A maneuvers is as follows: A rolling velocity is encountered, either intentional or unintentional, which exceeds the critical value and the airplane diverges in yaw. This sideslip combined with positive yaw due to roll and with the positive dihedral effect increases the rolling velocity and the rate of divergence in yaw. Soon a sufficiently high rolling velocity is obtained to enter the stable region. In this region the two oscillatory modes have periods of about 1.4 seconds and 6 to 12 seconds. After the long period mode completes a half cycle, the sideslip goes through zero and the rolling velocity reverses. As the rolling velocity builds up again, the unstable region is once more traversed. Because of the ineffectiveness of the ailerons, the pilot is able to influence the motion only when the rolling is reversing; the sideslip angle is small and consequently the rolling moment caused by effective dihedral is low. This is only a very short period during each cycle.

As discussed previously in flight B, the rudder was apparently subject to sticking (the pilot was unaware of this condition because of the high-control friction) and an abrupt 7° rudder movement was applied. The rolling and yawing motions that would be produced by such a control input were calculated and are shown in figure 10. It can be seen that the roll velocity produced by such a control motion could easily exceed the critical rolling velocity discussed previously with relation to figure 10, possibly resulting in a yaw divergence. It is apparent, therefore, that in this condition, extremely careful flying is required.

Mention has been made of the large amount of rudder control required for trim with the X-1A. Figure 11 presents trim curves obtained from

[redacted]

flight B which indicate the rudder required increases to a maximum of about 8° at a Mach number of 1.95 while the aileron required is about 5°. Comparison of this trim curve with data obtained with power off shows that the right rudder is required only with power on, and therefore, the trim is probably required because of misalignment of the rocket engine thrust axis with the airplane center of gravity. It would be expected that, because of this out-of-trim condition, shutting off the rocket engines would impose a yaw disturbance on the airplane similar to a rudder kick of this amplitude. Figure 12 shows time histories of the measured quantities for flight C with conditions almost identical to those existing at the start of the uncontrolled motions of flight B, that is, $M = 1.97$; $h_p = 87{,}000$ feet. At the start of the time histories the airplane was in fairly steady flight, but when the rockets were cut off the airplane abruptly yawed and rolled to the right. Rapid control motions apparently prevented the development of the uncontrollable motions experienced in flight B. The rockets were cut shortly after the first pronounced rolling on both flights A and B, possibly aggravating the motions.

CONCLUDING REMARKS

On two flights of the X-1A airplane, one reaching a Mach number of about 2.44, the other a geometric altitude of about 90,000 feet, lateral stability difficulties were encountered which resulted in uncontrolled rolling motions of the airplane at Mach numbers near 2.0. Analysis indicates that this behavior apparently results from a combination of low directional stability and damping in roll and may be aggravated by high control friction and rocket motor misalignment. The deterioration of directional stability with increasing Mach number can lead to severe longitudinal-lateral coupling at low roll rates. The misalignment of the rocket motor could induce sufficiently high roll velocities to excite coupled motions. Adequate control of these motions was virtually impossible because of the high control friction. In the absence of rolling, poor lateral behavior might be expected at somewhat higher Mach numbers because wind-tunnel data indicate neutral directional stability at about $M = 2.35$.

High-Speed Flight Station,
National Advisory Committee for Aeronautics,
Edwards, Calif., July 7, 1955.

Hubert M. Drake
Aeronautical Research Scientist

Wendell H. Stillwell
Aeronautical Engineer

Approved: for C. J. Donlan
Hartley A. Soulé
Research Airplane Projects Leader

DY

[redacted]

APPENDIX

Determination of Maximum Mach Number and Maximum Altitude

Maximum Mach number for flight A.- The maximum recorded Mach number for flight A is shown in figure 6 at time 295.2 seconds to be $M = 2.467$. This value occurs during pitching and yawing oscillations with large angles of attack and sideslip being attained. The flow angularities in the region of the static pressure orifices caused large fluctuations in static pressure and indicated that the maximum Mach number could be considerably in error inasmuch as it occurred at a peak of the static pressure fluctuations. It was impossible to correct the static pressures in the normal manner from radar-tracking data because of a failure of the radar synchronization system during this flight.

To arrive at a reasonable value for maximum Mach number, an expanded time history of the Mach number data was plotted and a smooth fairing of the curve was made. The maximum Mach number indicated by the fairing was 2.435 with a scatter of the recorded Mach number data of ± 0.07 about this curve. The instrument accuracies for this Mach number and altitude introduce errors of less than ± 0.01 in Mach number, therefore, the accuracy of maximum Mach number was based upon the estimated accuracy of the fairing of about ± 0.07 in Mach number.

The maximum true airspeed corresponding to a Mach number of 2.435 ± 0.07 and for a standard atmosphere temperature was 1612 ± 50 mph.

Maximum altitude for flight C.- The maximum altitude attained by the X-1A occurred during flight C at about time 382.5 seconds of figure 12. The exact value of pressure altitude for standard NACA atmosphere was 88,580 feet with an uncertainty of about ± 300 feet for the recorder accuracy.

The maximum geometric altitude was obtained from radar-phototheodolite data that showed the maximum altitude to be 90,440 feet. These data were obtained at about the maximum operating range of the radar phototheodolite and the errors at these ranges are estimated to be ± 500 feet.

[redacted]

REFERENCES

1. Ankenbruck, Herman O., and Wolowicz, Chester H.: Lateral Motions Encountered With the Douglas D-558-II All-Rocket Research Airplane During Exploratory Flights to a Mach Number of 2.0. NACA RM H54I27, 1954.

2. Gracey, William, Coletti, Donald E., and Russell, Walter R.: Wind-Tunnel Investigation of a Number of Total-Pressure Tubes at High Angles of Attack. Supersonic Speeds. NACA TN 2261, 1951.

3. Zalovcik, John A.: A Radar Method of Calibrating Airspeed Installations on Airplanes in Maneuvers at High Altitudes and at Transonic and Supersonic Speeds. NACA Rep. 985, 1950. (Supersedes NACA TN 1979.)

4. Spearman, M. Leroy, and Robinson, Ross B.: The Aerodynamic Characteristics of a Supersonic Aircraft Configuration With a 40° Sweptback Wing Through a Mach Number Range From 0 to 2.4 as Obtained From Various Sources. NACA RM L52A21, 1952.

5. Phillips, William H.: Effect of Steady Rolling on Longitudinal and Directional Stability. NACA TN 1627, 1948.

[redacted]

TABLE I

PHYSICAL CHARACTERISTICS OF THE BELL X-1A AIRPLANE

Engine	Reaction Motors, Inc., Model E-6000-C4
Rating, static thrust at sea level for each of the four rocket cylinders, lb	1,500
Propellant	
Fuel	Denatured alcohol and water
Oxidizer	Liquid oxygen
Fuel feed	Hydrogen peroxide turbine driven pump
Weight:	
Gross weight, lb	16,487
Landing weight, lb	7,266
Center-of-gravity travel, percent mean aerodynamic chord	Maximum 21.16 percent full load to 19.55 percent empty
Overall height, ft	10.70
Overall length, ft	35.55
Wing:	
Area (including section through fuselage), sq ft	130
Span, ft	28
Airfoil section	NACA 65_1-108 (a = 1)
Mean aerodynamic chord, in.	57.71
Location (rearward of leading-edge root chord), in.	6.58
Aspect ratio	6.03
Root chord, in.	74.2
Tip chord, in.	37.1
Taper ratio	2:1
Incidence, deg	
Root	2.5
Tip	1.5
Sweepback (leading edge), deg	5.05
Dihedral (chord plane), deg	0
Wing flaps (plain)	
Area, sq ft	11.46
Travel, deg	60
Aileron	
Area (each aileron behind hinge line), sq ft	3.21
Travel, deg	±12
Horizontal tail:	
Area, sq ft	26
Span, ft	11.4
Root chord, in.	36.5
Tip chord, in.	18.25
Aspect ratio	5
Dihedral, deg	0
Sweepback at leading edge, deg	11.97
Stabilizer travel (power actuated), deg	
Nose up	4 ±1/2
Nose down	9 ±1/2
Elevator (no aerodynamic balance)	
Area, sq ft	5.2
Travel from stabilizer, deg	
Up	15
Down	10
Vertical tail:	
Area (excluding dorsal fin), sq ft	25.6
Root chord, in.	66.4
Tip chord, in.	21.3
Fin	
Area (excluding dorsal fin), sq ft	20.4
Sweepback at leading edge, deg	21.67
Rudder (no aerodynamic balance)	
Area, sq ft	5.2
Travel, deg	±15

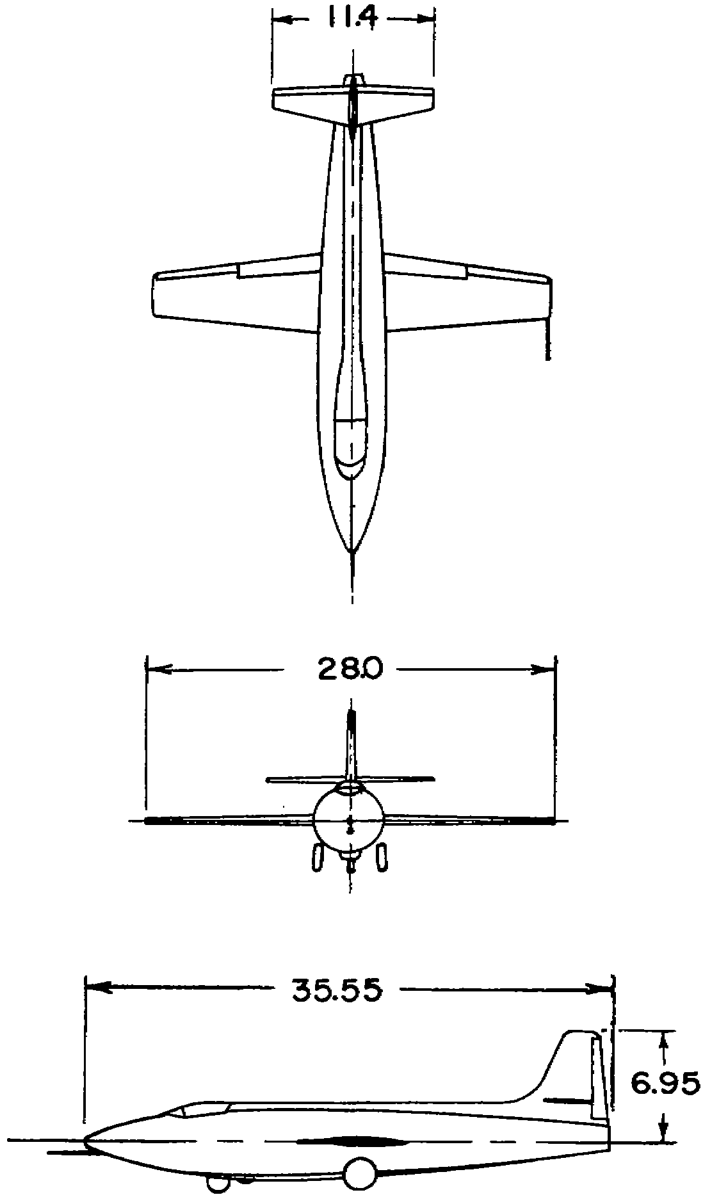
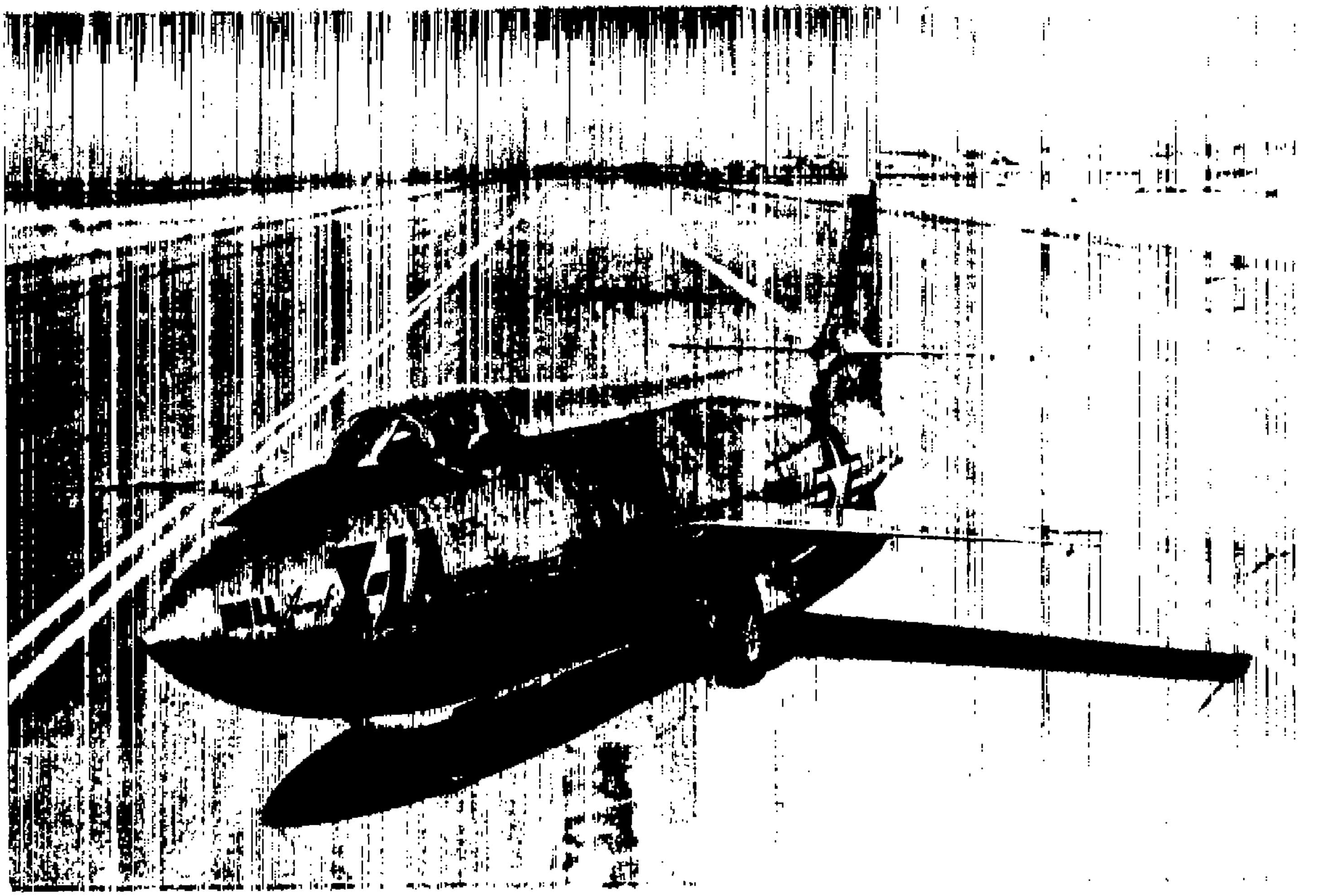


Figure 1.- Three-view drawing of the X-1A research airplane. All dimensions in feet.



L-89377

Figure 2.- Three-quarter front view of the X-1A airplane.

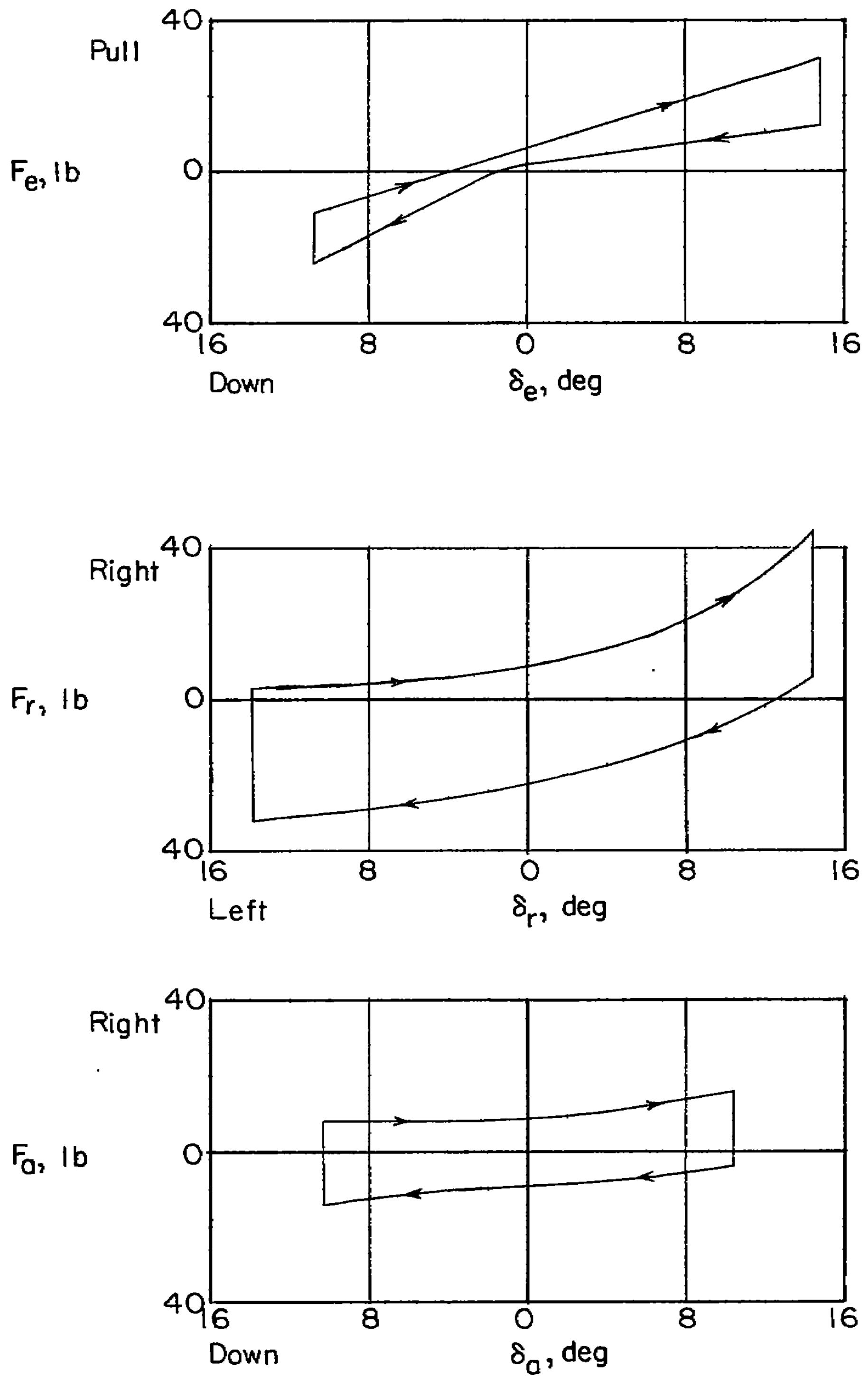
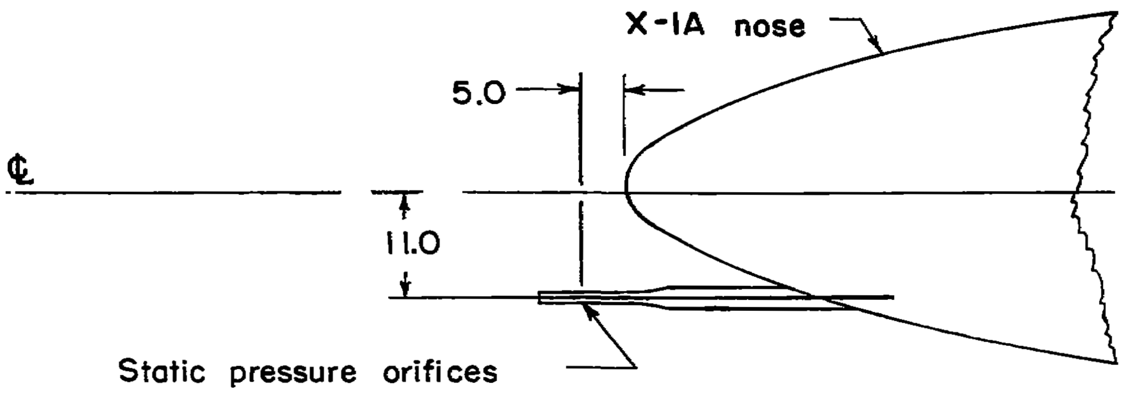
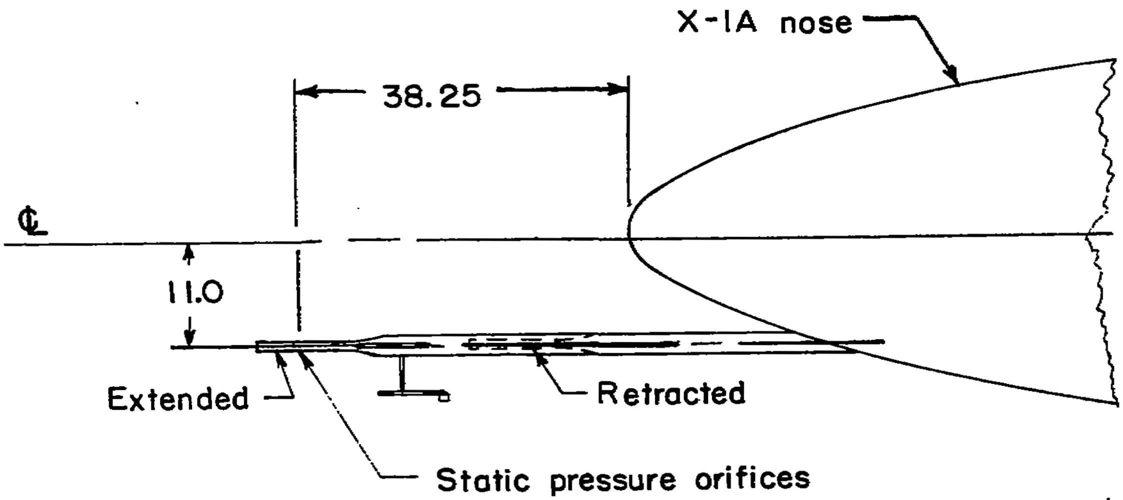


Figure 3.- Control forces required to deflect control surfaces under no load.

[redacted]



(a) Flight A.



(b) Flights B and C.

Figure 4.- Drawing of the pitot-static head installations. All dimensions in inches.

[redacted]

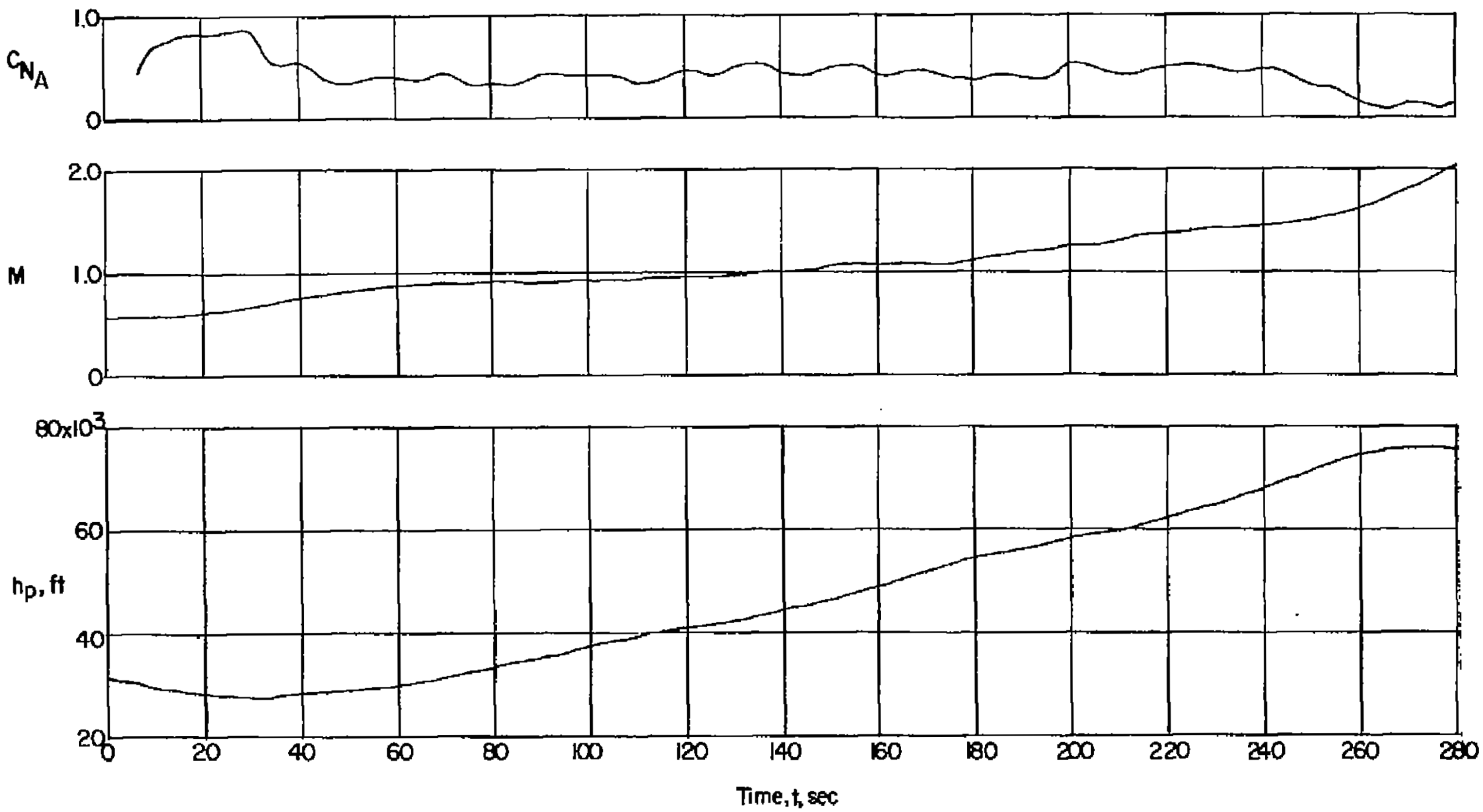


Figure 5.- Time history of flight to maximum Mach number (flight A).

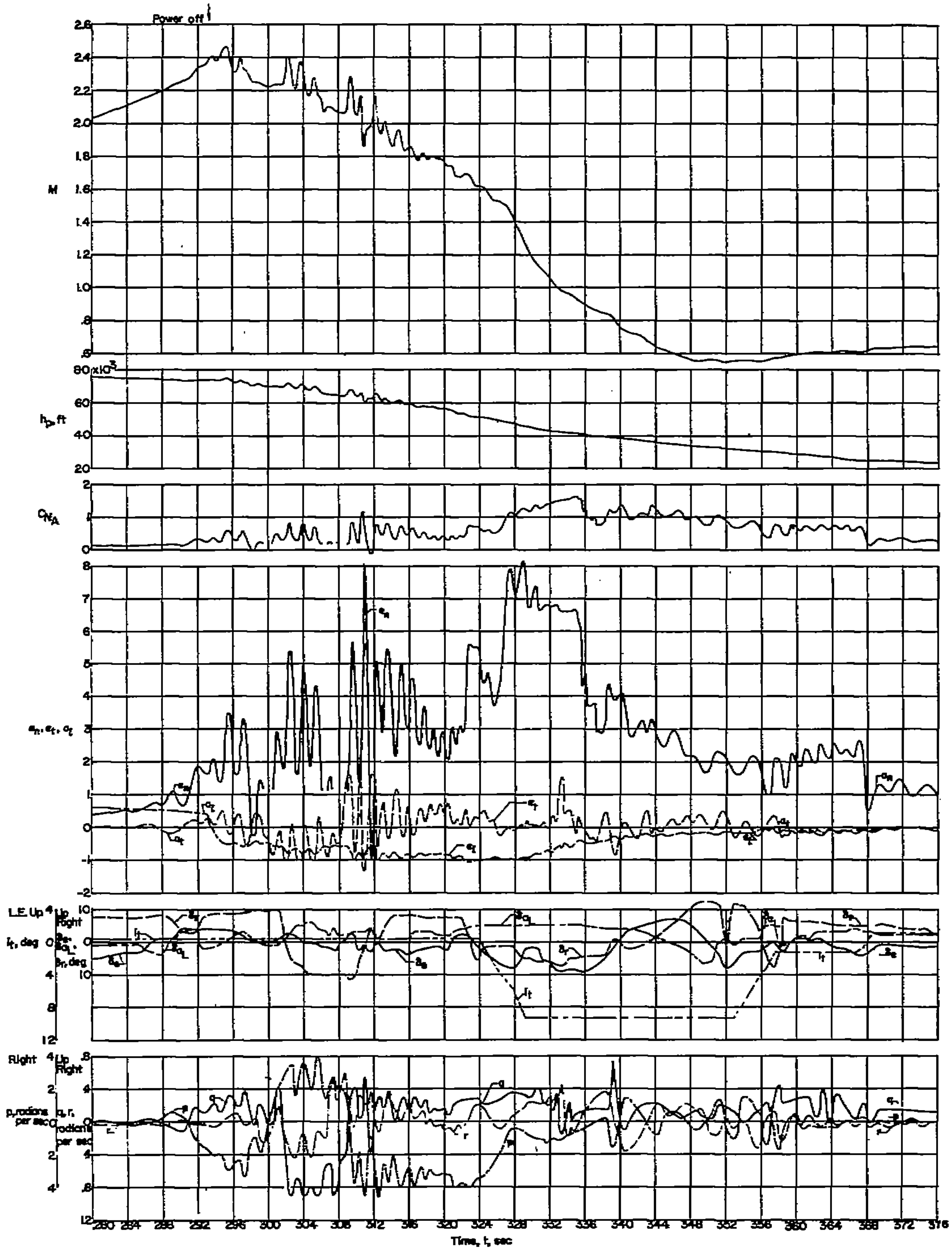


Figure 6.- Time history of measured quantities during uncontrolled portion of flight A.

[redacted]

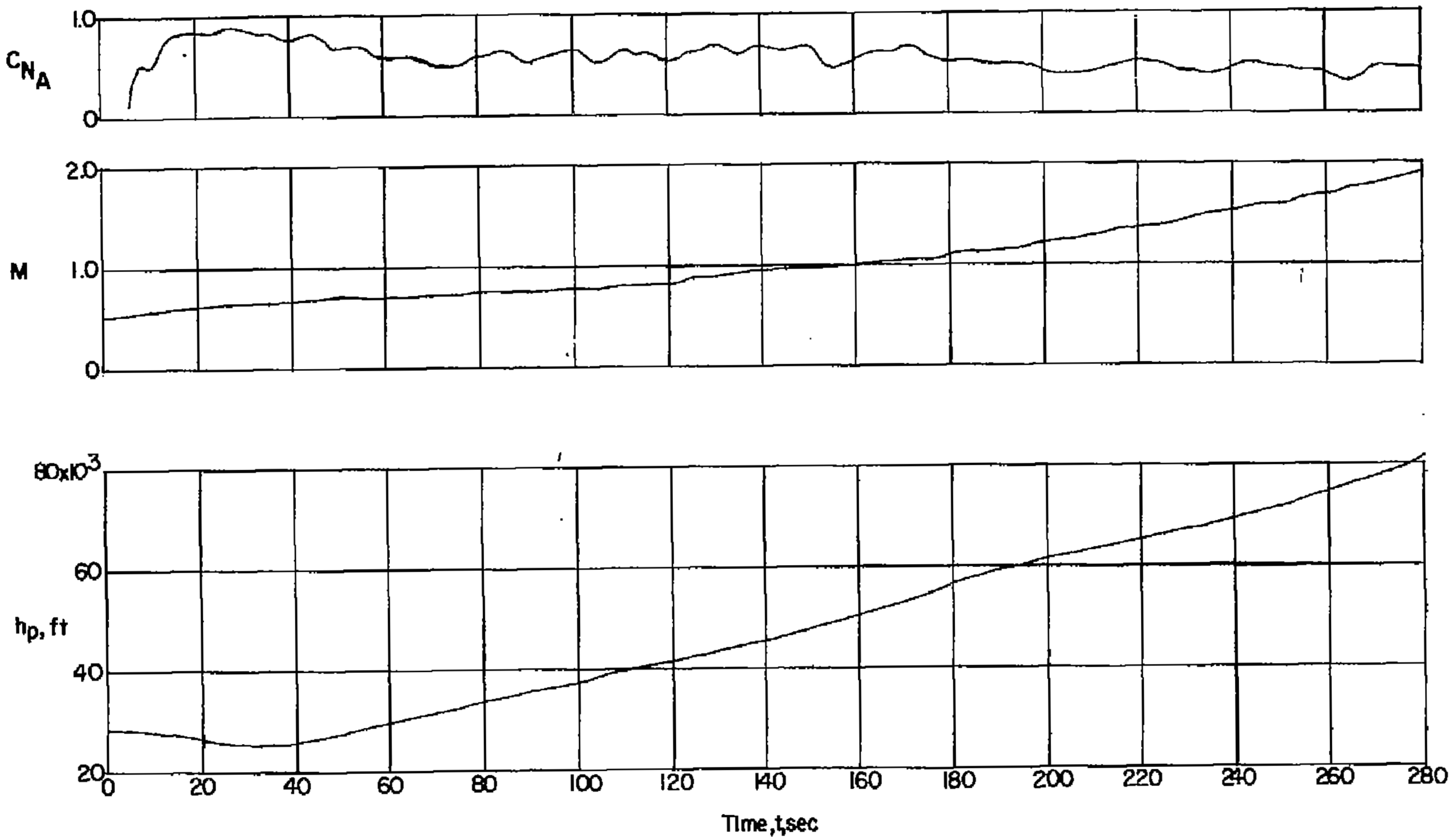


Figure 7.- Time history of flight to maximum altitude (flight B).

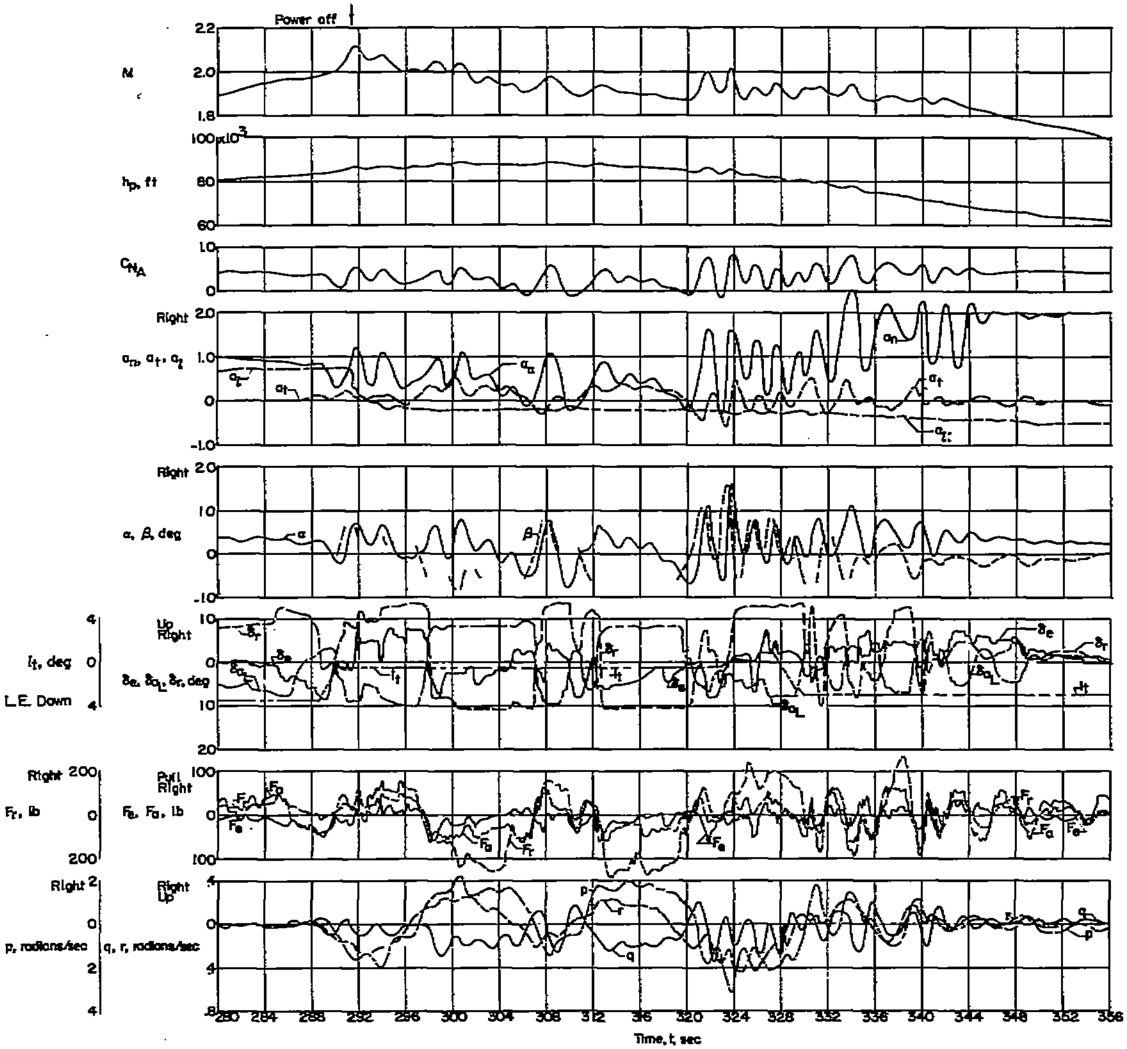


Figure 8.- Time history of measured quantities during uncontrolled portion of flight B.

[redacted]

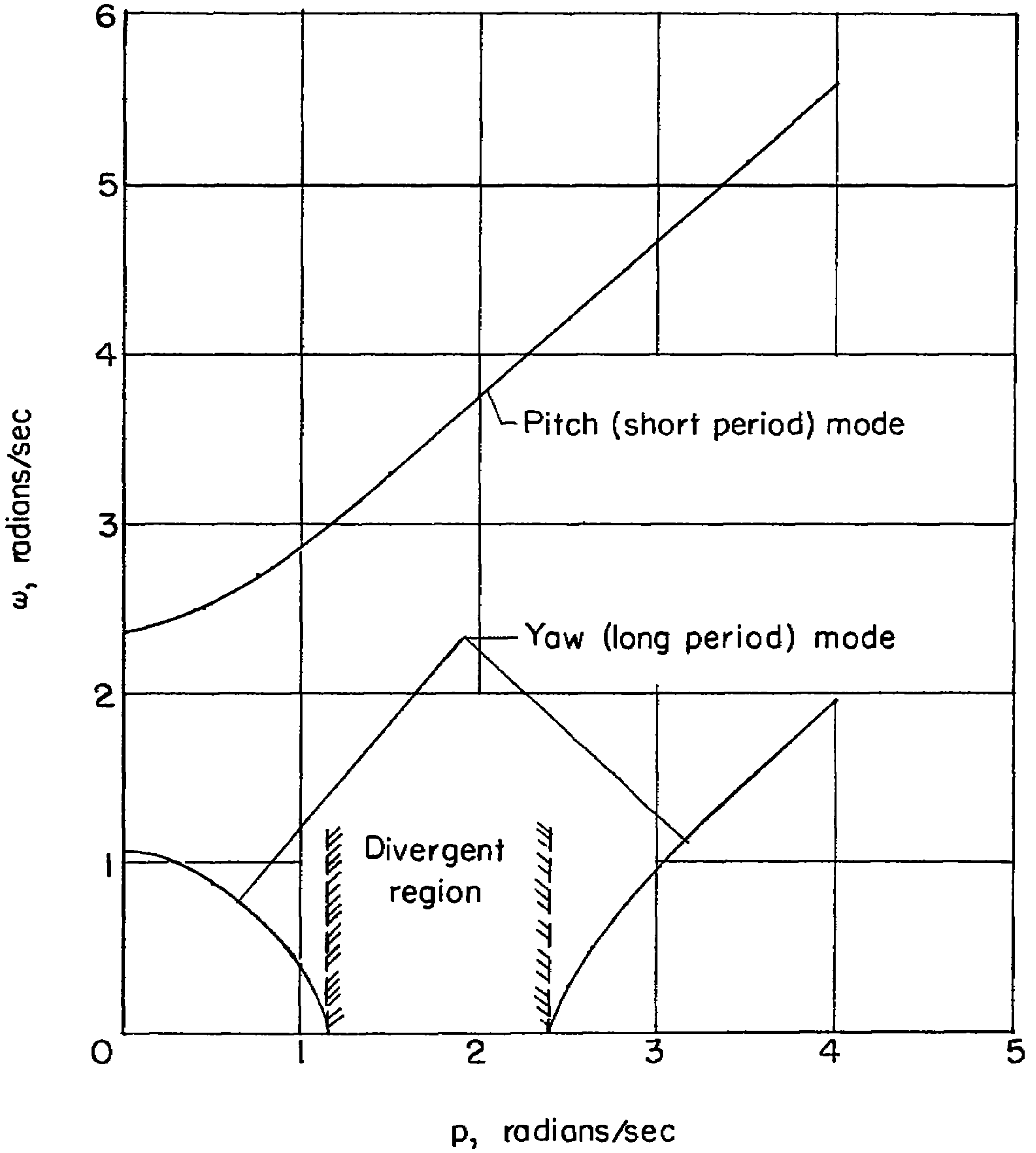


Figure 9.- Oscillatory characteristics of the X-1A as a function of rolling velocity at $M = 2.0$; $h_p = 90,000$ feet. Assumed inertias $I_X = 1,981$ slug-ft^2, $I_Y = 17,400$ slug-ft^2, $I_Z = 18,700$ slug-ft^2.

[redacted]

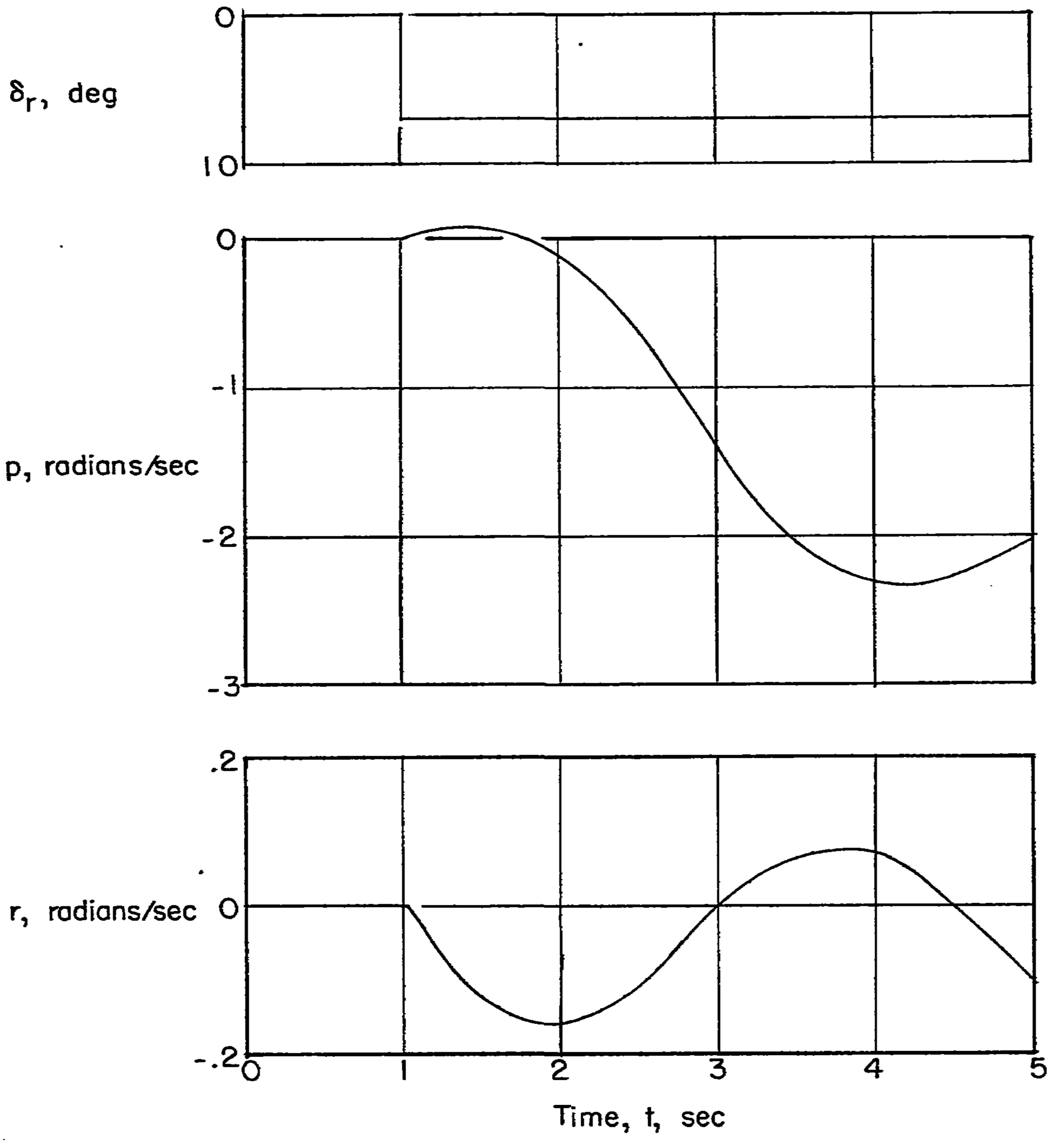


Figure 10.- Calculated response to 7° rudder step input for the X-1A airplane at $M = 1.97$; $h_p = 85{,}000$ feet, $C_{l_\beta} = -0.0012$ and $C_{n_\beta} = 0.0008$.

[redacted] [redacted]

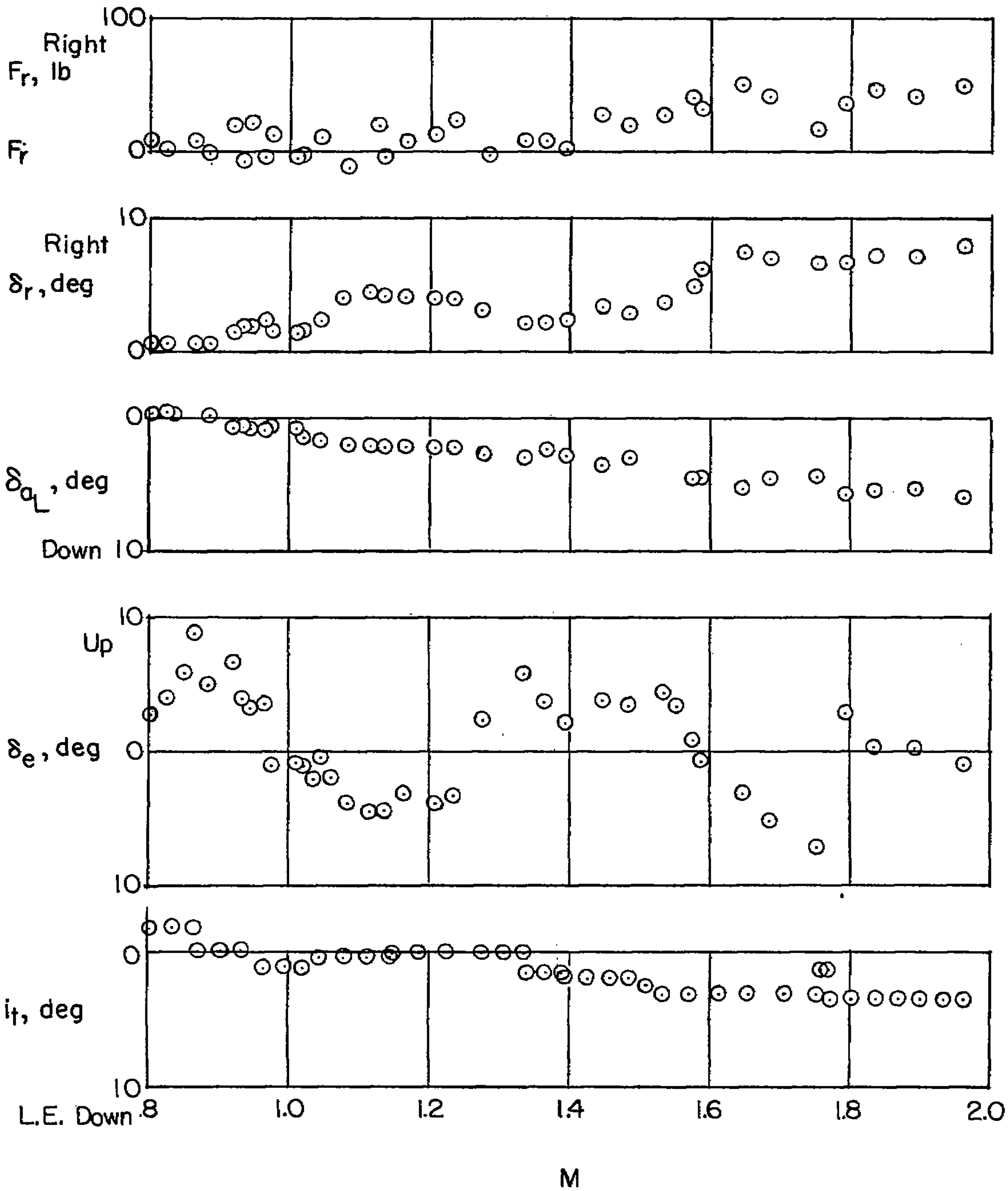


Figure 11.- Variation of elevator, rudder, aileron, and stabilizer position, and rudder force with Mach number for the power-on portion of flight B.

[redacted] [redacted]

[redacted]

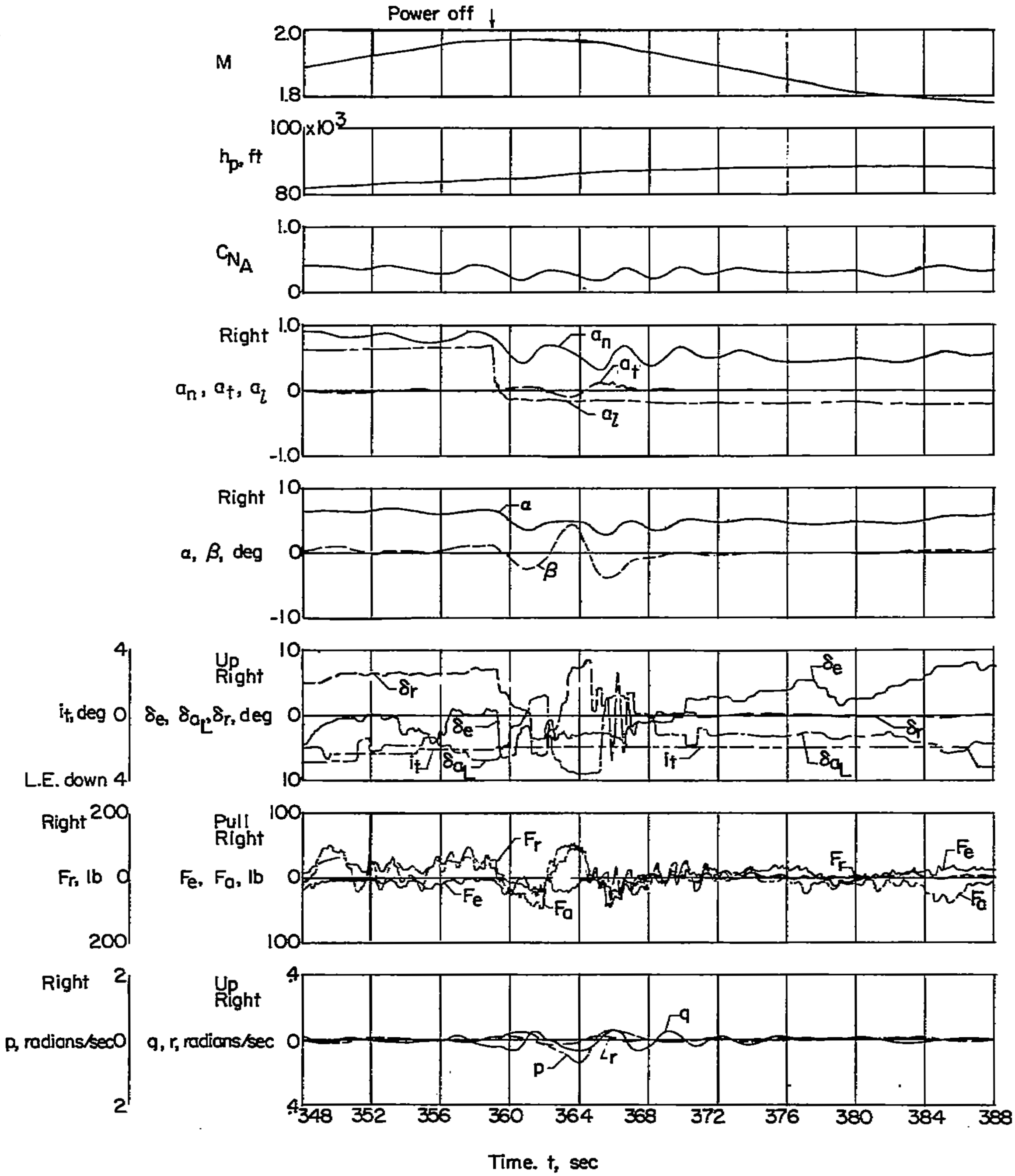


Figure 12.- Time history of all quantities measured during flight C.

[redacted]